Study of the internal stresses in the capsular bag after the implantation of an intraocular lens and the causes of its dislocation

Carlos Sagarra López

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Supervisors: Professor Paulo Rui Alves Fernandes
Doctor Maria Filomena Jorge Ribeiro

Examination Committee

Chairperson: Professor Fernando Manuel Fernandes Simões
Supervisor: Professor Paulo Rui Alves Fernandes
Members of the committee: Carlos Alberto Matinho Marques Neves
João Orlando Marques Gameiro Folgado

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Abstract

Cataract surgery is very common and the majority of these surgeries are successful and are really fast. However, some people who are operated of cataracts have problems after a while (after 5-7 years or more): they suffer a dislocation of the IOL (intraocular lens), and still is not clear the reasons why this happens.

The aim of this work is to find out what is causing this problem. And in order to reach the objective, the study was done creating a 3D finite element model of the capsular bag, the intraocular lens (IOL) and the zonular fibres in ABAQUS.

About this study there are a few things to take into account: the capsular bag is considered a membrane which is the most similar model to the real one, also the ligaments were modelled as wires and the IOL was made of three different material: polymethyl methacrylate (PMMA), silicone and natural material of human lens as a control group.

The results show that the stresses on the capsular bag and also on the lens are asymmetric so the stress is not distributed in the same directions than before the surgery, what is interesting information in order to advance on this project.

There are studies those show that after cataracts surgery the pressure inside the eye it is the same or even lower than before this operation, which means that is not a crucial aspect to take into account as it is for example the deterioration of the tissues of human eye.

Keywords: accommodation, finite elements, intraocular lens, dislocation, cataracts

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Abbreviations

CB: capsular bag

ECCE: extracapsular cataract extraction

FDA: Food and Drug Administration

FE: finite element

ICCE: intracapsular cataract extraction

IOL: intraocular lens

LEC: lens epithelial cells

PCO: posterior capsule opacification

PMMA: polymethyl methacrylate

ZF: zonular fibres

2D: two dimensional

3D: three dimensional

PCO: posterior capsule opacification

1. Introduction

Eye structure plays an important role in determining the procedure carried out during an eye surgery and the history of its study has been ongoing for several centuries. It was in 1611 when Johaness Kepler published results of his calculations of the eye, concluding that is in the retina - and not in the crystalline - where the image of what we're seeing is created.

Then in 1793 William Porterfield described the mechanism of accommodation, what is crucial to understand all the forces inside the eye. The accommodation is the mechanism by which the eye changes refractive power by altering the shape of the lens in order to focus objects at variable distances.

However, before that, in 1656 Werner Rolfinck who was a german doctor was first man ever who has showed clearly cataract is an opacification of the crystalline but this discovery wasn't taken seriously.

In addition, focusing on the surgery, at the middle of the XVIII century, there were the first intracapsular cataract extractions (ICCE), which was the first way to operate cataracts. Then, during the XIX century they started to improve the extracapsular cataract extraction (ECCE) - which is the current procedure – reaching its right application at the beginning of the XX century.

This intraocular lens (IOL) was improved year by year until IOLs that are used nowadays, with specific materials and different shapes but the most common shape is an IOL with two thin legs that press the inside of the surface of the capsular bag (CB) as can be seen in figure 1.

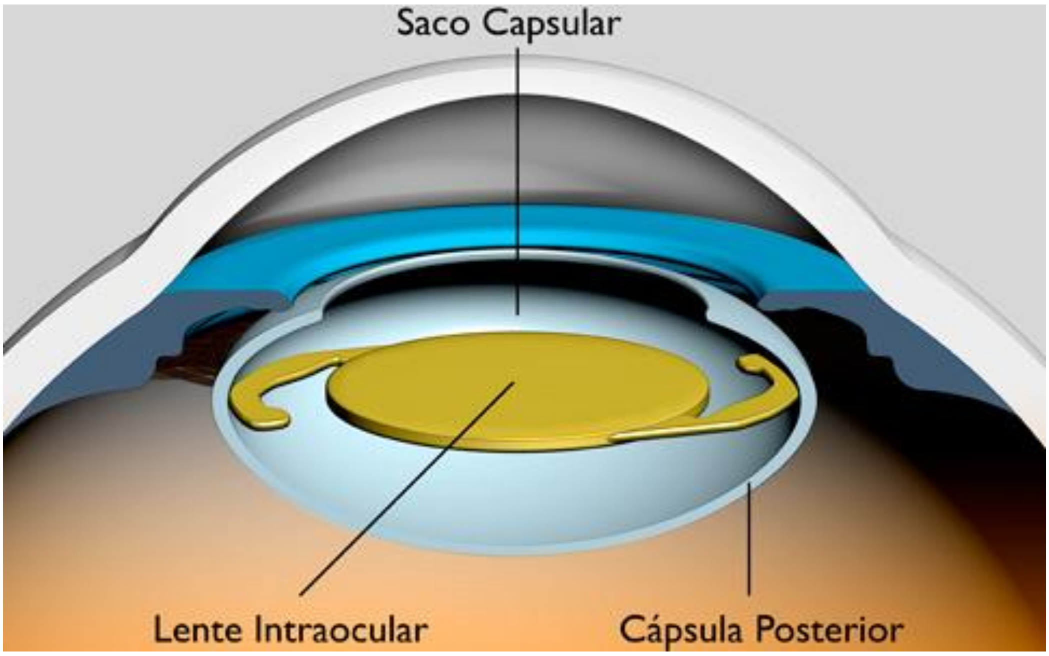

Figure 1. IOL inside capsular bag after cataract surgery

Finally, nowadays there are studies about different issues regarding cataract surgery, and one of them is try to understand why after some years after this surgery, some people have dislocations of the lens.

1.1 Motivation and work objective

As mentioned above, cataract surgery is an old operation. However, over time doctors and investigators were discovering new things about the eye, and one of them is accommodation.

Accommodation is probably one of the most interesting and important mechanism of human body. It is a very fast system that focuses – as figures 2 shows - what the human brain wants to see. Accommodation is thus a process that takes place thousands of times a day, so that means that there are tissues working very fast and lot of times per day.

Consequently, there is a compulsory question: what works that hard? And the answer, nowadays, is easy: ciliary body. And after this answer, the curiosity is: what are these tissues made of? Which are their mechanical properties? So that investigate to find these properties were crucial in order to build eye models and understand what happens inside the eye.

Lot of models were built in the past, but different between them. The following text from Atchison DA *et al*. (2016) sums up why and how are the models built: Many optical eye models give accurate predictions only for small fields of view. If aberrations and image quality are important to consider, such 'paraxial' model eyes must be replaced by finite element model eyes incorporating features such as aspheric surfaces, tilts and decentrations, wavelength-dependent media and curved retinas. Many optical model eyes are population averages and must become adaptable to account for age, gender, ethnicity, refractive error and accommodation. They can also be customised for the individual when extensive ocular biometry and optical performance data are available. We consider which optical model should be used for a particular purpose, adhering to the principle that the best model is the simplest fit for the task.

Following that, the objective of this work is to analyse how the CB, zonulars fibres (ZF) and IOL reacts to accommodation process.

A dislocated lens is a lens that has moved out of position because some or all of the supporting ligaments have broken. Some people are born with conditions that can cause weak ligaments and are prone to having a dislocated lens (Harvard Publishing, 2014). ZF are therefore crucial in the study of accommodation-related issues, and so are CB and IOL because of their proximity and interaction with the ligaments. These three parts are modelled in ABAQUS in order to work on dislocation problems.

To achieve the aim of this work, the distribution of the stresses is monitored and compared for different materials of the IOL in order to assess their influence. Forces, boundary condition and constraints are applied and the FE model calculates all stresses values and distribution.

1.2 Thesis structure

This project was developed with the mechanical engineering department of Instituto Superior Tecnico (IST) department and ophthalmologists from Hospital Da Luz. This first chapter is a short introduction to the project, but beside this one there are 4 more chapters. Firstly, the objective of the project is presented. Also a short summary of the history of the medical problem is explained. In addition to this a brief introduction to eye models is presented.

In chapter 2 the eye anatomy, including all its parts and how it works human vision are presented. Also accommodation, which is crucial in order to understand the eye, is explained. Furthermore there is an introduction to IOL explaining its design, biocompatibility and related problems. Finally cataract surgery and causes of cataracts are explained.

Chapter 3 includes the computational model for the eye (CB, IOL and ZF) and the mechanical properties used on it with ABAQUS following scientific data.

Chapter 4 includes the results of the stresses obtained and their distribution. Also there is a comparison of the results among the materials chosen for the IOL. Furthermore these results, the methodology are discussed, including a slight self-criticism.

In chapter 5, the last one, conclusions and hypothesis about the causes of the problem on which the work is based indicating how it could continue this project are presented.

Annex A illustrates mechanical properties of CB, ZF and IOL used for this project and also some other measures used for the design of the model.

2. The eye

2.1 Eye structure

Vision occurs when lights enters through the pupil. In fact, it depends on important structures (like cornea and iris) of the eye how good the vision is. The main aspect to have a perfect vision is to let enter the appropriate amount of light towards the lens.

The eye works in a very similar way than a camera as shows figure 2. Lens "refracts" incoming light onto the retina, which is made up by millions of specialised cells (rods and cones) which together transform into electrical energy the image. That electrical energy is sent to the optic disk on the retina and transferred via electrical impulses along the optic nerve to be processed by the brain.

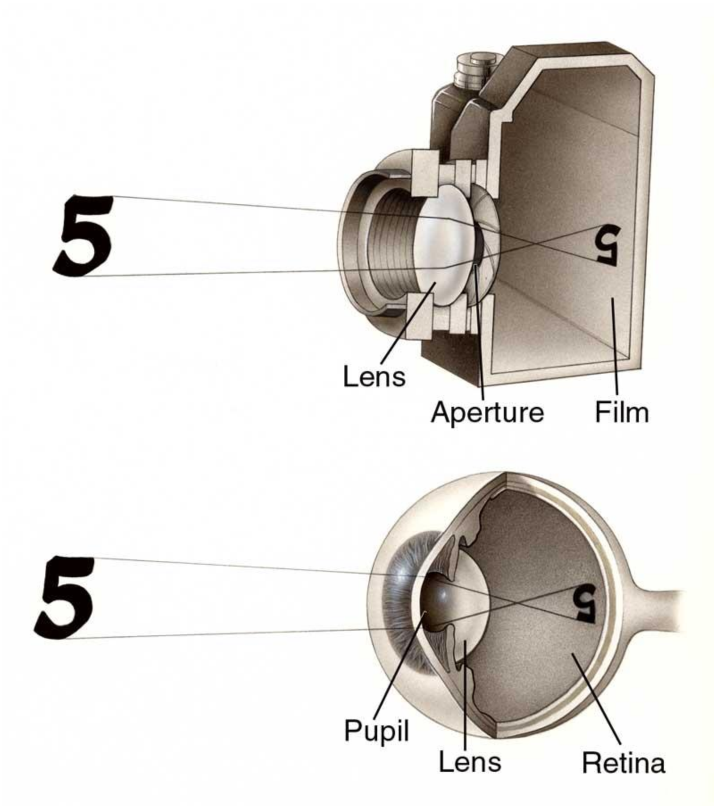

Figure 2. Eye works like a camera

The structure of the eye (showed in figure 3) consists of several parts:

- Aqueous humor: The fluid produced in the eye.

- Ciliary body: Part of the eye that connects the choroid to the iris.

- Retina: light sensitive layer that lines in the interior of the eye. It is composed of light sensitive cells known as rods and cones. Human eye contains approximately 125 million rods and between 6 and 7 million cones. The first are useful in dim light, on the other hand the second are useful in bright light and, of course, to distinguish colours.

- Lens: a transparent structure situated behind your pupil. It is enclosed in a thin transparent capsule and helps to refract incoming light and focus it onto the retina. A cataract is when the lens becomes cloudy, and a cataract operation involves the replacement of the cloudy lens with an artificial plastic lens.

- Cornea: the transparent circular part of the front of the eyeball. It refracts the light entering the eye onto the lens, which then focuses it onto the retina. The cornea contains no blood vessels and is extremely sensitive to pain.

- Pupil: the circular opening in the centre of the iris through which light passes into the lens of the eye. The iris controls widening and narrowing (dilation and constriction) of the pupil.

- Optic nerve: leaves the eye at the optic disc and transfers all the visual information to the brain.

-Iris: regulates the amount of light that enters your eye. It forms the coloured, visible part of your eye in front of the lens. Light enters through a central opening called the pupil.

- Choroid: the middle layer of the eye between the retina and the sclera. It also contains a pigment that absorbs excess light so preventing blurring of vision.

- Optic disc: the visible (when the eye is examined) portion of the optic nerve, also found on the retina. The optic disc identifies the start of the optic nerve where messages from cone and rod cells leave the eye via nerve fibres to the optic centre of the brain. This area is also known as the 'blind spot’.

- Capsular bag: a sack-like structure, where the lens is located, remaining within the eye following extracapsular cataract extraction or phacoemulsification. The implanted IOL is placed within this structure to recreate the usual state.

All the description of eye structure comes from moorfields.nhs.uk (2017).

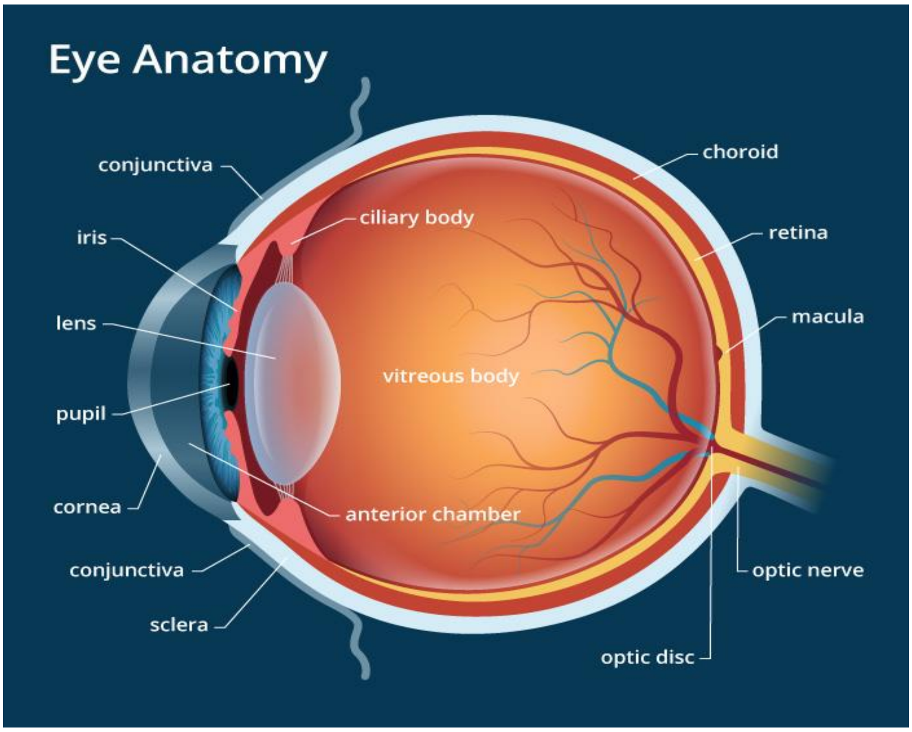

Figure 3. Eye anatomy. The lens is located inside the capsular bag which is held by the ciliary body

2.1.1 How human eye works? Accommodation

Accommodation is the process in which the eyes see objects at different distances and maintain clear images of the objects by the convergence and divergence of light. Figures 4 and 5 illustrate this mechanism.

When the lens is in focus, its stress increases through the equatorial ZF and when ciliary body contracts, the ZF located along its equator increase their tensile strength. This results in the steepness of the central surface of the lens, an increase in thickness of the lens and a flattening of the lens edges. Figure 4 shows the model in nonaccommodated stage, where the equatorial (EZ) and anterior zonules (AZ) are in tension, while posterior zonules (PZ) are relaxed.

The ocular structures involved in this process include the ciliary muscle (ZF), lens and pupil.

Ciliary muscle: it holds the lens with the suspensory ligaments and also adjusts the optical power or shape of the lens during accommodation.

Lens: is held by the suspensory ligament and has a diameter of 10.4 mm and height of 4 mm in an adult. These measurements vary due to change in the lens structure during accommodation and aging.

Pupil: constricts to prevent light rays that have diverged from touching the retina and caused blurred vision.

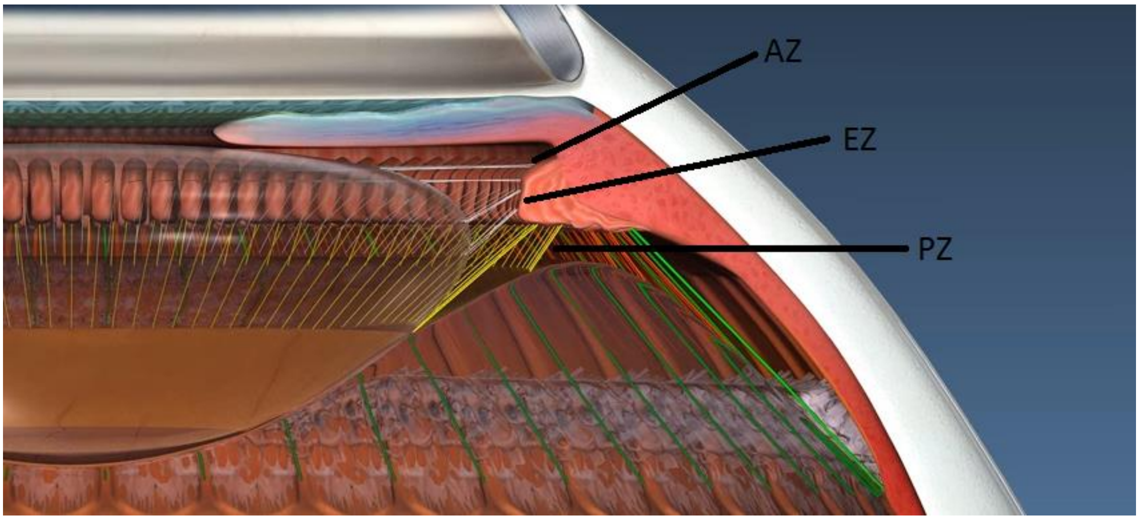

Figure 4. Model which anterior zonules (AZ), equatorial zonules (EZ) and Posterior Zonules (PZ) during accommodation (nonaccommodated stage)

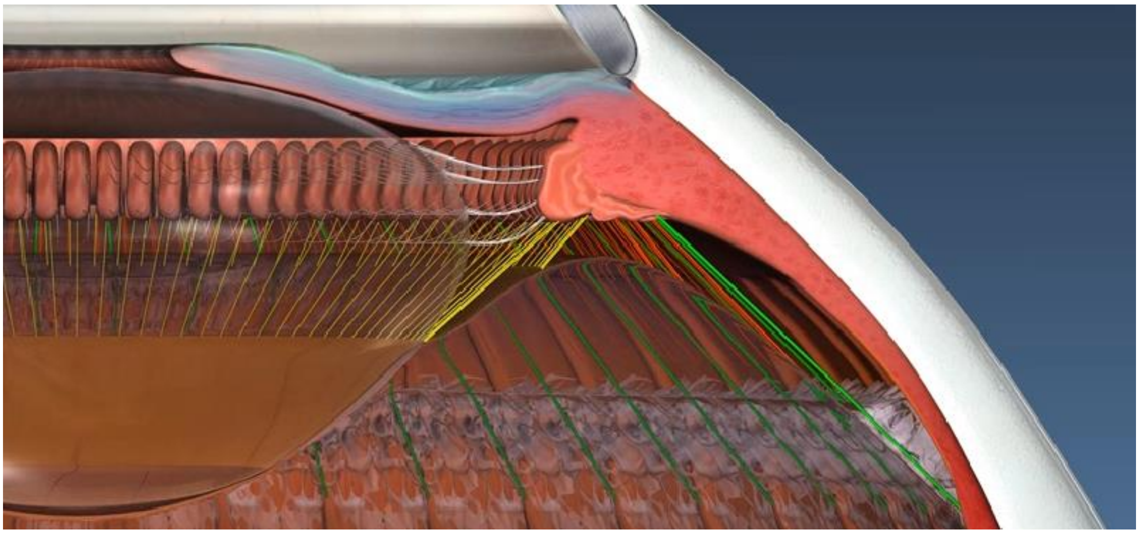

Figure 5. Model in accommodated stage

2.2 Cataracts and surgery

Cataract is a clouding of the lens, which lies behind the iris and the pupil.

Cataracts are the most common cause of vision loss, most of all in people over 40 years old, and may end up with blindness if it is no treated in time.

There are 3 types of cataracts (Bailey *et al.* 2017):

- Subcapsular cataract: starts with a little cloudy surface at the back of the lens. It occurs just under crystalline lens capsule. People who take high doses of steroids or with diabetes have a greater risk of developing this type of cataract.

- Cortical cataract: consist on cloudy areas which develop on crystalline lens cortex, in the periphery of the lens. Also people with diabetes have a greater risk of developing this type of cataract.

- Nuclear cataract: is the most common cataract among old people. It occurs in the central zone of the lens. This type of cataract takes long time developing.

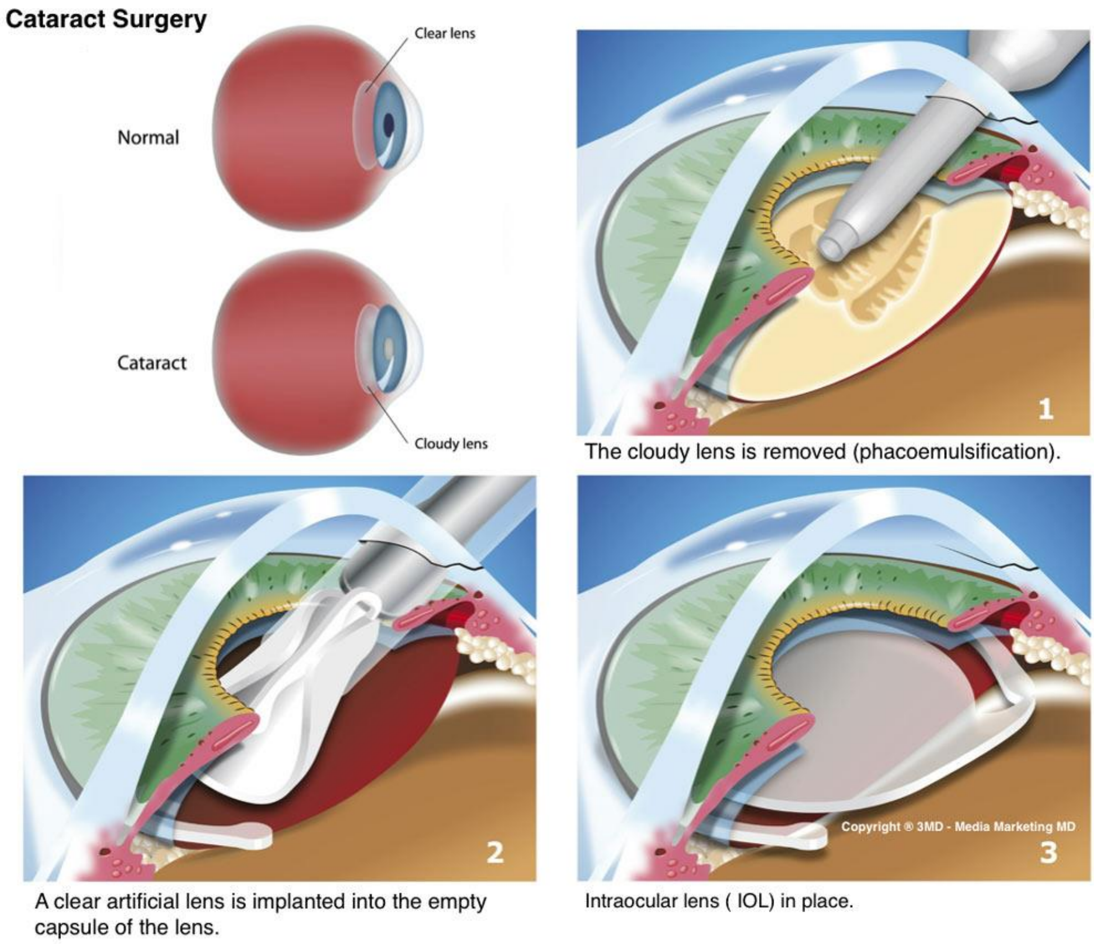

Figure 6. Steps of cataracts surgery

Cataracts surgery consists on remove the blurred lens by a cut in the CB and enter the IOL as figure 6 illustrates.

Causes of cataracts:

Human eye lens is mostly made of water and protein. This protein keeps the lens clear and let pass the right amount of light through it. But as we age, some of the protein may clump, building some dense groups which start to cloud a small area of the lens. And then, over time, this area may become bigger, what is the cataract. Figure 7 shows that progress.

There is no clear verdict on why cataracts occur, but there are some risk factors to take into account that are a common denominator among people who suffer from cataracts. Some of these risk factors are:

- Genetics (family history)

- Obesity

- Diabetes

- Smoking

- Prolonged use of corticosteroid

- High myopia

- Hypertyension

- Significant alcohol consumption

- Hormone replacement therapy

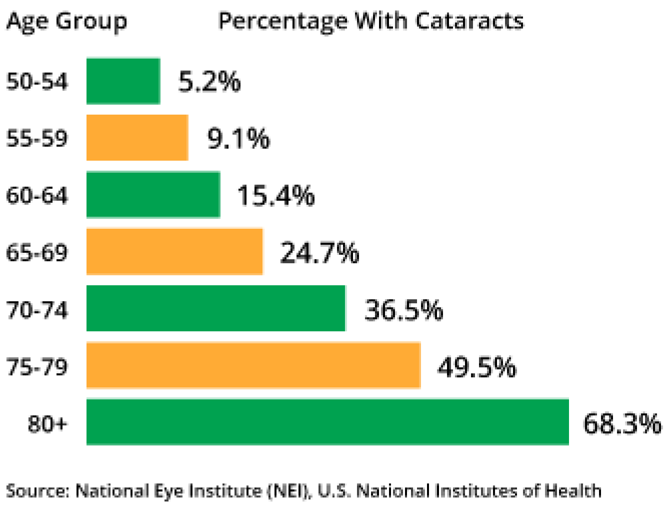

Figure 7. Percentage of each age group with cataracts

2.3 IOL (intraocular lens)

IOLs are medical devices that are implanted inside the eye to replace the natural lens of the eye during cataract surgery.

FDA - which is responsible for protecting the public health by ensuring the safety, efficacy, and security of human and veterinary drugs, biological products, and medical devices - approved IOLs at the beginning of the 80s. Before the use of this device, everyone who had cataracts surgery had to wear very thick eyeglasses in order to see after the surgery.

Today there is a wide variety of premium IOLs to choose from. The one which fits better depends on every single person: lifestyle and specific visual needs are crucial to find which type of IOLs fits the best.

2.3.1 Size and materials

Despite the average CB only has a diameter of about 10.4 mm, the variability of the lens size is quite large. It can be from 9.8 to 10.9 mm. For this reason and the fact that the bag ovalizes after lens implantation, especially in the case of weak zonules, most IOLs are oversized for the bag.

The earliest IOLs were made of polymethylmethacrylate (PMMA) despite it has a relatively low PCO (posterior capsule opacification) rates but it is not foldable, and nowadays foldable materials such as hydrophobic acrylic, hydrophilic acrylic (or hidrogel) and hydrophobic silicone are the main materials of the current IOLs.

- Foldable hydrophobic acrylic:

The most used material group. The materials have very low water content, high refractive index, and usually a high memory (tends always to reshape to the initial shape), which also makes the material suitable for the haptics of a monobloc open-loop IOL.

One of the drawbacks of this material group has been intralenticular changes. Small water inclusions in the optic material called glistenings can occur in hydrophobic materials, predominantly seen with the Acrysof material, which is an hydrophobic one. Over time, the glistenings can increase, but evidence to this date does not indicate any effect on visual function.

- Hydrophilic acrylic

It is a quite heterogeneous material group and has high water content. The water content between IOLs varies widely and can be as high as 38%.

One problem with some hydrophilic acrylic lenses of different companies was opacification of the optic material due to calcification. However, must be said that it hardly ever occurs this kind of problems.

The main problem of this material probably is that is more prone to develop posterior capsule opacification (PCO) than the other two materials.

- Silicone

It was the first material available for foldable IOLs. Despite being a good material, especially its PCO blocking effect, it cannot be used for a monobloc open-loop lens, and this is a problem. Nowadays is hardly used.

2.3.2 Design

During the past decade it has become clear that optic edge design plays an important role in the prevention of PCO. When the Acrysof lens (Alcon) was introduced in the early 1990s, several studies showed that PCO development was significantly less than with other IOLs. This first was attributed to the acrylic material and to the surface properties of the IOL. Later it could be shown that the sharp-edge design of the lens seemed to be the key factor for this effect. The sharp IOL edge was a result of the manufacturing process, and its blocking effect on LEC migration, therefore, rather coincidental. Further studies confirmed that the rectangular shape of the IOL rim with its sharp edges, in combination with the acrylic material, was in fact the main reason for the reduced formation of PCO. Unfortunately, sharp optic edges of IOLs may also have disadvantages. In some cases with implantation of lenses with a rectangular edge shape combined with a high refractive index, such as found with the Acrysof lens, an increased incidence of persistent edge-glare phenomena was reported. Designs are well illustrated in figure 9.

Optic geometry:

The majority of IOLs are symmetric, what means that the radius of curvature of the front and back surface are exactly the same. There are some asymmetric IOLs but implies some problems when implanting the new lens. Most IOLs have a full-size effective optical zone of 6 mm in the main range.

2.3.3 Biocompatibility

The performance of an IOL is determined by several factors such as the surgical technique, the perioperative treatment, the IOL biomaterial and design, and the host reaction to the lens.

The cellular reaction seen on an IOL is an important indicator of the IOL's biocompatibility. On the one hand, it consists of macrophages in the form of small, round cells and foreign body giant cell on the IOL surface. On the other hand, the cells are LECs after the capsule comes into contact with the foreign body IOL. Accordingly, the biocompatibility of an IOL can be divided into two parts—the uveal and the capsular reaction.

Uveal biocompatibility is defined as the reaction of the uvea to the IOL. As a result to the surgical trauma and the IOL, monocytes and macrophages migrate through the uvea's vessel walls into the aqueous and then onto the IOL surface. Monocytes transform into small, round cells and macrophages transform into epithelioid and foreign body giant cells that are responsible for the phagocytosis of debris. These cells constitute the natural immunological process in a foreign body reaction.

Capsular biocompatibility is defined as the reaction of LECs and the capsule to the IOL material and design. This includes LEC ongrowth, anterior capsule opacification, and PCO. The LECs residing on the posterior side of the anterior capsule, the so-called A-cells, can proliferate onto the IOL optic from the anterior capsular rim and lay down collagen which results in whitening of the capsule as well as contraction of the capsule, which in turn may cause rhexis contraction or even phimosis, decentration of the IOL, or buttonholing of the IOL.

Design and biocompatibily information was found in Findl (2009).

Figure 8. Transdifferentiating lens epithelial cells of the anterior capsule shortly after surgery

PCO (posterior capsule opacification)

PCO is a common problem after cataract surgery with implantation of an IOL. It resulted from the transition from intracapsular cataract extraction (ICCE) to ECCE, where the posterior lens capsule is left intact during surgery. Patients with PCO suffer from decreased visual acuity, impaired contrast sensitivity and glare disability.

Clinically, two different components of PCO can be differentiated, namely a regeneratory and a fibrotic component. Regeneratory PCO is much more common; it is caused by residual LECs from the lens equator region, the so-called E-cells, migrating and proliferating into the space between the posterior capsule and the IOL –as shows figure 8 - forming layers of lens material and Elschnig pearls. Fibrotic PCO is caused by LECs from the anterior capsule that undergo transformation to myofibroblasts and gain access to the posterior capsule, causing whitening and wrinkling of the capsule. As described above, this can lead to decentration of the IOL and hinder visualization of the peripheral retina. Both components of PCO lead to a decrease in visual function when they affect the central region around the visual axis (Findl, 2009).

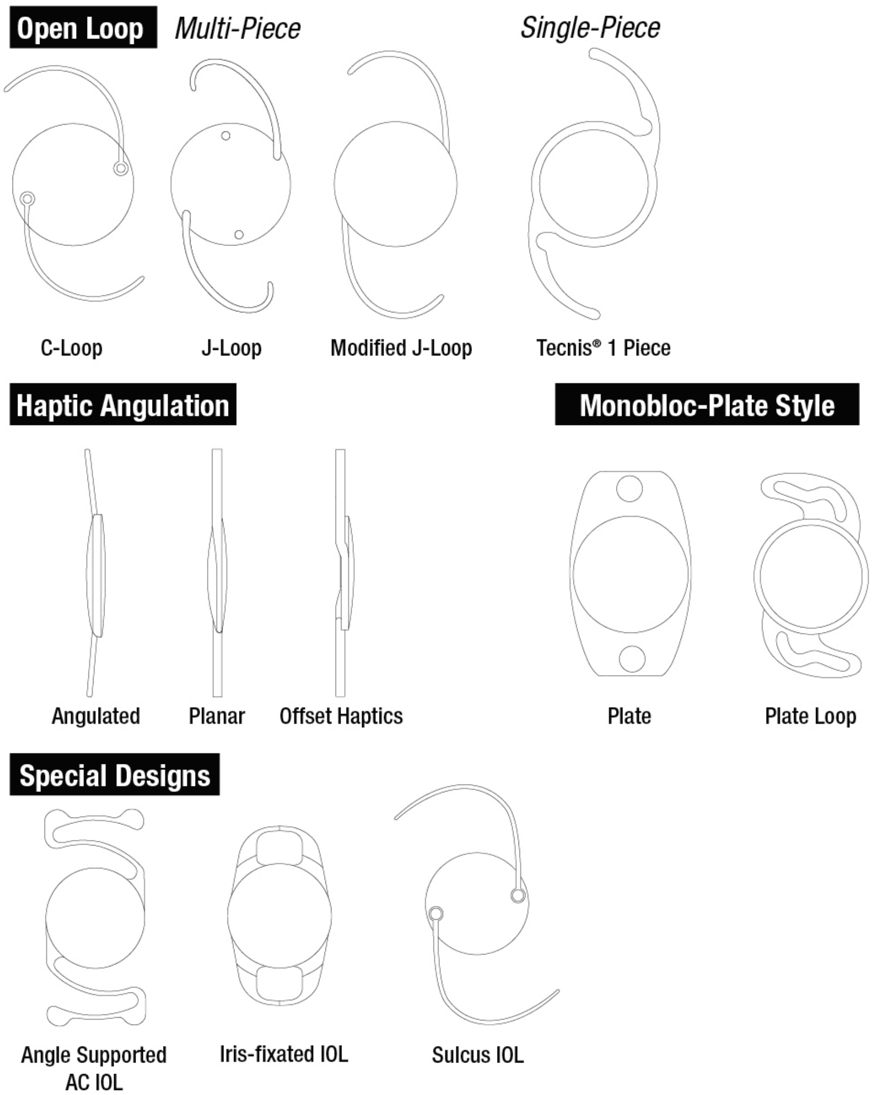

Figure 9. Types of intraocular lenses

3. Material and methods

3.1 Introduction

A three dimensional FE model of a lens replacement solved in Abaqus/CAE 2016 was used to carry out this project. This numerical model was used to evaluate the pressures exerted on the eye, more concretely in the ligaments, the CB and the lens. The FE model geometry consists of the IOL, the CB - where the lens is located - and the ZF. The sum of all these components makes up the model used to work on the project.

The study is focused on the forces taking place during accommodation process, which can be divided into two stages: accommodated (figure 5) and non-accomodated stages (figure 4). In the first one, the posterior zonules are exerting force and in the second one, anterior and equatorial zonules are exerting force. In order to build the model, the non-accommodated stage was chosen.

All the parts of the model were modelled with a 3D FE mesh, as we can see in the figure 10.

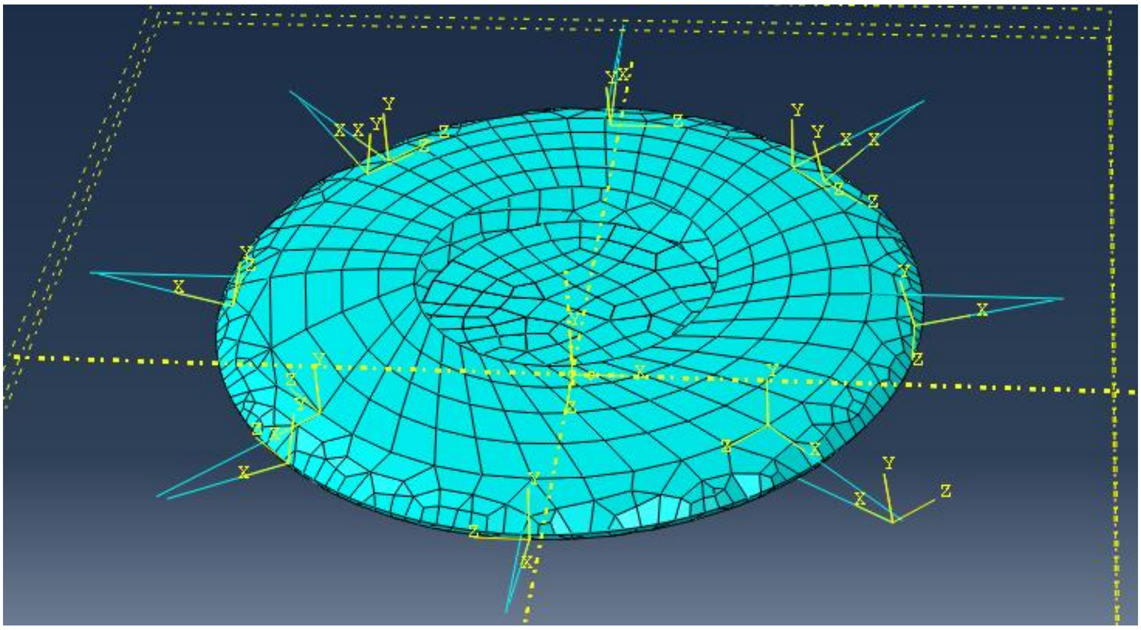

Figure 10. Mesh of the model with 1416 nodes

During the construction of FE approximations, a discretisation of the parts was necessary. That discretisation was made using tetrahedral and triangular elements for all these parts.

To determine what pressures are present inside the eye, three different materials were considered.

In one model the lens was completely natural; this is the mechanical properties of the original lens. That was made as a control model.

Then, a second model was made of PMMA, which is the material, among the three, that requires more force to deform it elastically, so is the one with higher Young modulus.

The third one is silicone, which has mechanical properties very similar to the crystalline lens material, both Young modulus and Poisson's ratio.

Noteworthy, the two mechanical properties used to distinguish the different materials were the Young modulus and Poisson ratio.

- Young modulus is a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression. Sometimes referred to as the modulus of elasticity, Young's modulus is equal to the longitudinal stress divided by the strain.

- Poisson ratio is a ratio of the relative contraction strain (transverse, lateral or radial strain) normal to the applied load to the relative extension strain (or axial strain) in the direction of the applied load.

3.2 Finite element model

3.2.1 Introduction

At the beginning, two different models were built. One 2D model and one 3D model.

The first model (2D) was made in order to have a first approximation to results. However, with this model there was a problem: it was necessary to made the CB as a membrane, but a membrane in ABAQUS can only be used in 3D models, so after trying to draw the CB as a solid homogeneous with its mechanical properties, it was seen that it could not show the reality and the results did not show anything even close to real forces and stresses in a normal eye, so this model was rejected.

The second model (3D) was done with the purpose of finding much more relevant results than the previous one and as closest to the reality as possible.

This model has 3 distinguished parts as mentioned above: CB, IOL and ligaments (ZF). These parts are made of specific material which has its own mechanical properties. The CB and the ligaments are natural parts of human body, so are original while the IOL is artificial. According to Weeber and Rob G.L. van der Heijde (2008) - who at the same time is documented by Krag (1996) and Van Alphen (1991) - in their article the CB and the ZF have a theoretical constant Young modulus and Poisson ratio despite aging. So it seems that the crystalline lens is the only part which suffers a significant change over time on its Young modulus, and it is not a minor change.

3.2.2 Mechanical properties

Firstly, the location point in the lens (closer or further away from the centre) makes the difference, because while in the periphery of the lens the change between 20 years old and 60 years old is from 0.100kPa to 6.248Kpa, so 62 times bigger, in the very centre of the lens the change at the same age difference is from 0.043 kPa to 108.544 kPa, so 2524 times bigger.

Secondly, as it was said above, over time the Young modulus increases. That means that as humans get older, the lens is less deformable or, put another way, it is necessary to apply much more force to elastically deform the lens as the person becomes older. This is because the lens starts to lose its properties and starts to be more rigid and less malleable.

So to decide which Young modulus would be chosen it was taken the data (Annex A) of 60 year-old, because is the closest age to the average age of people who have cataract surgery, which is higher than 60 years old. Then, in order to choose among the different location points in the lens – from the centre to the periphery – an average value was chosen, this is 50 kPa. There are two reasons for that: first Young modulus values changes a lot in the eye between the centre and the periphery but this study is not focused on the original lens material but on the other two materials and besides that it changes very little the results (less than a thousandth of Pascal) and also the main stress and the one that interests the most for the study is in the CB and ligaments.

Regarding PMMA and Silicone, which information was taken from UB website (ub.edu/CMEmaterials), they have Young modulus generally higher than the original lens. Silicone is a widely used material because of its resistance to warm and humidity, and also has mechanical properties which make it very compatible in human body. The Young modulus of silicone is between 0.005 GPa and 0.02 GPa. PMMA has a Young modulus of between 2.24 GPa and 3.38 GPa. These values explain why nowadays it is not common to use, because it is necessary to apply a lot of force to elastically deform and in consequence, it is very difficult to fold, which is crucial in cataracts surgery nowadays.

Poisson ratio, in that case, is strongly related to the explained above. So there is an inversely proportional connection with these materials. PMMA, which has the highest Young modulus, has the lowest Poisson ratio, and the original lens which has the lowest Young modulus has the highest Poisson ratio.

The Poisson ratio of the crystalline lens is 0.495. That means that changes a lot its shape easily on all axes. Really close to this value is silicone, which has a Poisson ratio of between 0.47 and 0.49. Very far from these values is PMMA with a Poisson ratio of between 0.384 and 0.403 (table 3 and 4 of Annex A). This clarity, then, a nearness as far as mechanical properties between silicone and the original lens, unlike PMMA that is far from being similar to them.

Much simpler was to find in literature and apply the mechanical properties of the CB and the ZF. These ligaments have a Young modulus of 0.35 MPa and a Poisson ratio of 0.47 and CB has a Young modulus of 1.5 MPa and the same Poisson ratio than zonular ligaments (Weeber et *al.*, 2008).

All this data (from CB, ZF and crystalline lens) was used with the same purpose than this project has, to analyze by ABAQUS some reactions of the eye applying several loads.

3.2.3 Dimensions and design

The eye model made for this project tried to reproduce exactly the real dimensions (ReserchGate, 2017) of the elements included in the study.

The length of the ZF varies depending on the connecting part - posterior, equatorial or anterior - of the CB. But an average value was taken and this is a length of 2.5 mm. The thickness of these ligaments is between 40 µm of diameter which is the thickness of posterior and equatorial zonules and 50 µm which is the thickness of anterior zonules. As in nonaccommodated stage the force is only exerted by anterior and equatorial zonules, as it shows figure 4, both measures were taken.

The dimensions of the CB have more details to consider. In order to explain, it would be necessary to distinguish two main parts in the CB: anterior and posterior. The distance between the posterior and the anterior part right in the middle of the CB (dashed line figure 11) is 3.5 mm. Then the radius of curvature of the posterior part is 6 mm while the radius curvature of the anterior part is 11 mm. Thus, the anterior part is more flat and the posterior one more domed. The radius of the CB is more or less 10.4 mm. Also the thickness has been considered appropriate for the CB that is 8 µm what is an average among its thickness which is according to Weeber et al. (2008) 13 µm at anterior pole and 3 µm thickness at posterior pole.

Finally, the third part is IOL and there are plenty of options to build this model because of the high quantity of different models on the market. The basic measures to reproduce the real IOL are two: on one hand the diameter of the total IOL - taking into account its legs – has to be the same as the CB to exert pressure on it, what is what happens in reality, and this is 10.4 mm. On the other hand the diameter of the centre of IOL, which is known as optical zone (circular part), is 6 mm. Also it has to be said that IOL thickness is 0.2 mm (Naeser *et al.*, 1993).

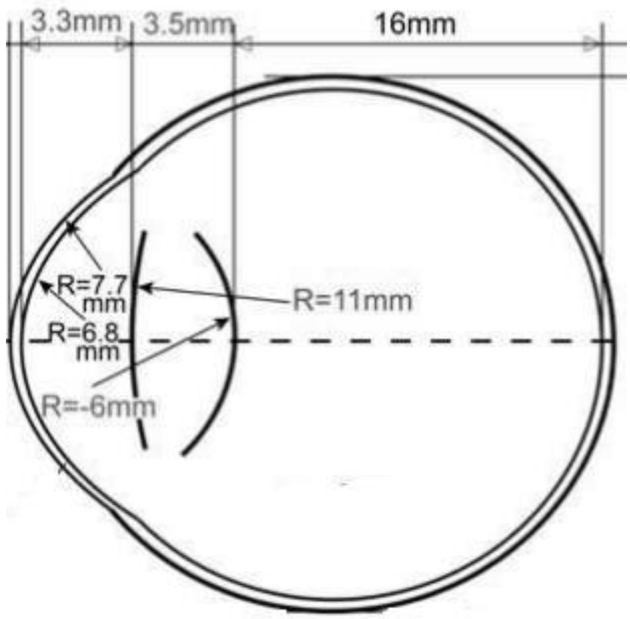

Figure 11. Dimensions inside the eye

3.2.4 Mesh design

It is very important to obtain accurate results which reflect the reality and in order to reach that, the well discretisation of the surface of the three parts of the model is crucial.

The initial geometry is defined with the default values that ABAQUS considers. This geometry requires a good refinement of the mesh such that the discretized surface accurately represents the current surface area. So the more nodes there are the better result is obtained.

And a study was done in order to verify that. Figure 12 illustrates a convergence study performed for the model of this project with a lens made of silicone, although the material does not make the difference as mentioned above, and of course I does not affect to this graphic the material because all the data is taken with the same material.

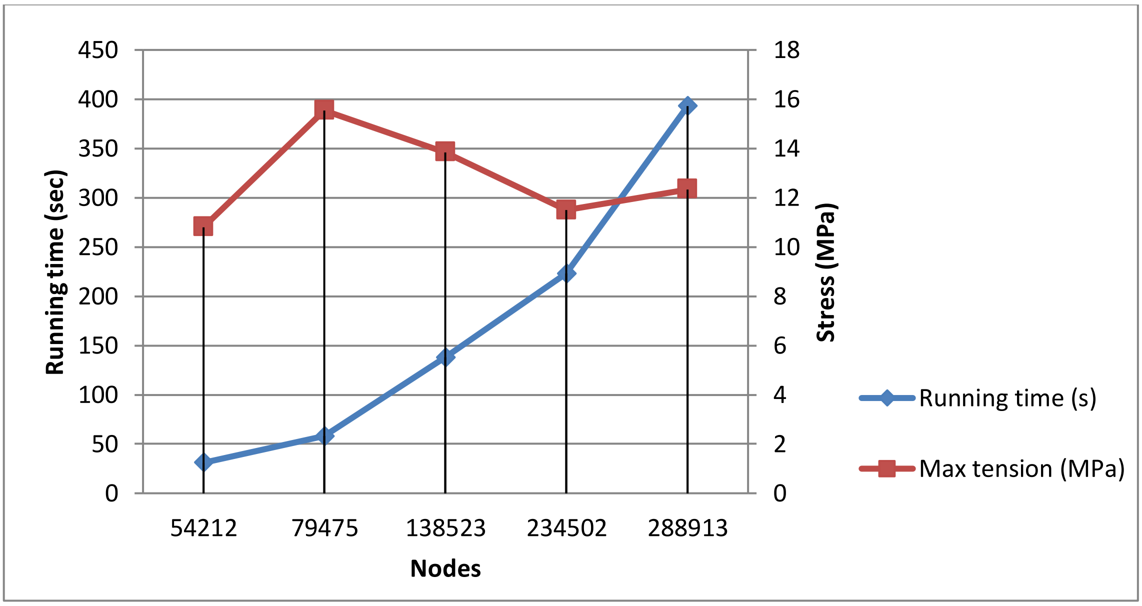

Figure 12. Convergence of the maximum pressure in the capsular bag with finite element mesh refinement

The convergence is influenced by mesh refinement in terms of the number of the FE used to achieve the solution. The figure 12 shows five different approximations. The nodes are the total nodes, so is the sum of nodes in CB, ligaments and IOL.

The maximum stress or pressure values are obtained with 79475 nodes, but it's not a significant value. Approaching, the most accurate result that has been obtained is 12.34 MPa, while the two previous approaches were 11.49 MPa – with 234502 nodes - and 13.84 MPa – with 138523 nodes – so the definitive result is an intermediate value. The differences of distribution of stresses can be observed in figures 13 and 14.

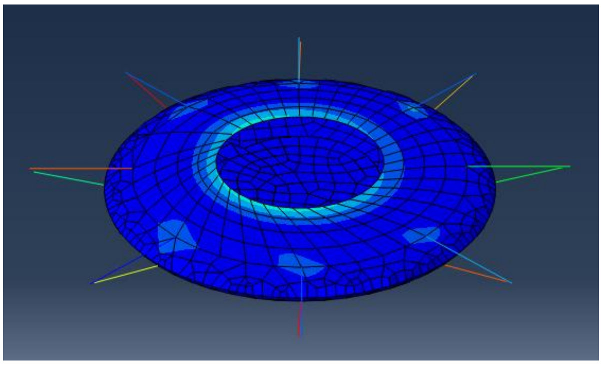

Figure 13. Model with 1416 nodes

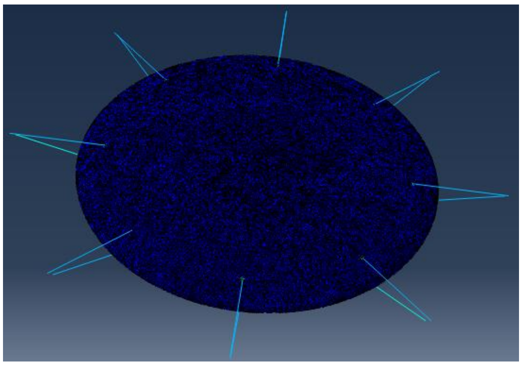

Figure 14. Model with 288913 nodes

By observing the running time it is a fact that number of elements of the mesh is directly related with time spent processing. The result is an exponential graphical line what means that there is not a relation of nodes-time, so 1 node does not equal time unit.

3.2.5 Materials and loads

ABAQUS gives lot of options to choose materials and different properties.

The three parts of the model (CB, ZF and IOL) are made of isotropic materials, which are materials that have the same physical properties in all directions. Also, all the parts are elastic and Young modulus and Poisson ratio have been considered.

The CB was built as a membrane shell because it does not have any bending stiffness and thus it bends almost without any resistance.

IOL was built as a solid homogeneous element. It is definitely an element that opposes resistance, especially its legs.

ZF were built as truss beam. The section is a beam because there is not another valid option. From that starting point two options could be chosen: beam or truss. A beam is designed to withstand mainly the stresses due to bending. That means the cross section of a beam is exposed to both tension and compression simultaneously due to bending. On the other hand, trusses are only used when the loads must be transferred axially (no bending takes place). Truss is chosen because the forces on the ZF are axial.

About the intersections, there are sixteen tie constraints, one for each ZF with the interior surface of CB. A tie constraint provides a simple way to bond surfaces - or a surface with a node - together permanently. In addition, there are more tie constraints between the exterior surfaces of the legs of the lens and the inner surface of the CB. Finally, there more tie constraints in order to connect both parts – anterior and posterior - of the CB.

Regarding to boundary conditions, firstly it has to be said that not every boundary condition is applied in order to improve the work or to fix some parts but also because sometimes some elements require boundary conditions because the loads are not in full in the axis in which it is ordered, but it is a sum of forces of the 3 axes and with which it can suffer some deviations that ABAQUS notifies that as an error. In addition, it is important to mention that all the nodes or surfaces which have an encastre boundary condition will not perceive the pressures and will not be notified by ABAQUS, so they will be imperceptible.

The two models can be differentiated by their way of generating results: the first one, called model A, is done with the purpose of measuring the pressures applied on the CB and the second one, called model B, focuses on the pressures applied on the ZF. Both models monitor the pressures suffered by the lens.

- Boundary conditions in model A: following the figure 15 there are three different boundary conditions:
  - 1: the circular surface which is the result of the cut in cataract surgery has a displacement boundary condition to avoid movement in the Y axis to make sure that all displacements will be horizontal, which is the reality, and also to avoid some errors that ABAQUS notified.
  - 2: the 16 ZF are fixed at the ends because it is a static model, so if these ligaments were not fixed, the CB would move so ABAQUS would notify an error.
  - 3: A specific axis was considered for every ligament which do not follow the X, Y or Z axes of the global one.
  - 4: A displacement/rotation condition was applied to avoid movements in any directions but the ligament’s one. Also was used the rotation option to not let it rotate in any axis the ligament. That condition was just because an ABAQUS error.

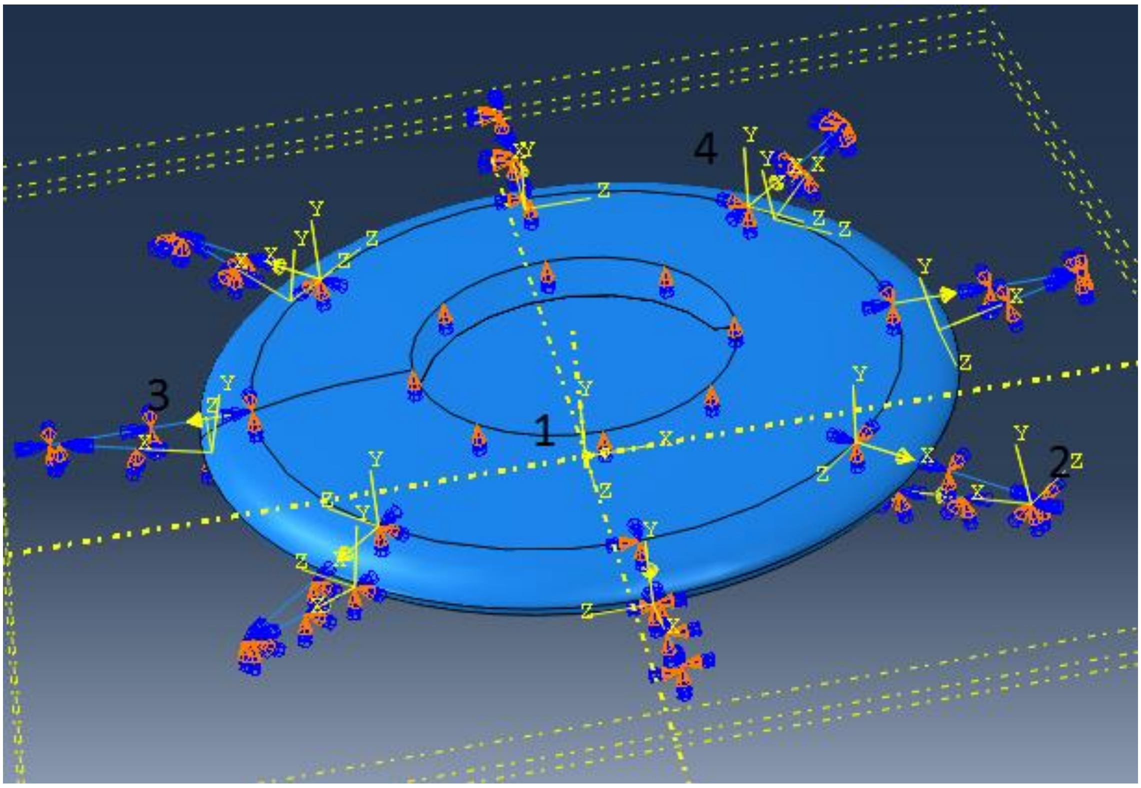

Figure 15. Boundary conditions of the model A

- Boundary conditions in model B: following the figure 16 there are two different boundary conditions:
  - 1: A displacement/rotation condition was applied to avoid movements in any directions but the ligament's one. Also was used the rotation option to not let it rotate in any axis the ligament. That condition was just because an ABAQUS error.
  - 2: An encastre boundary condition was applied to fix the whole CB in order to avoid the movement because it is a static model so it is compulsory to fix some parts.

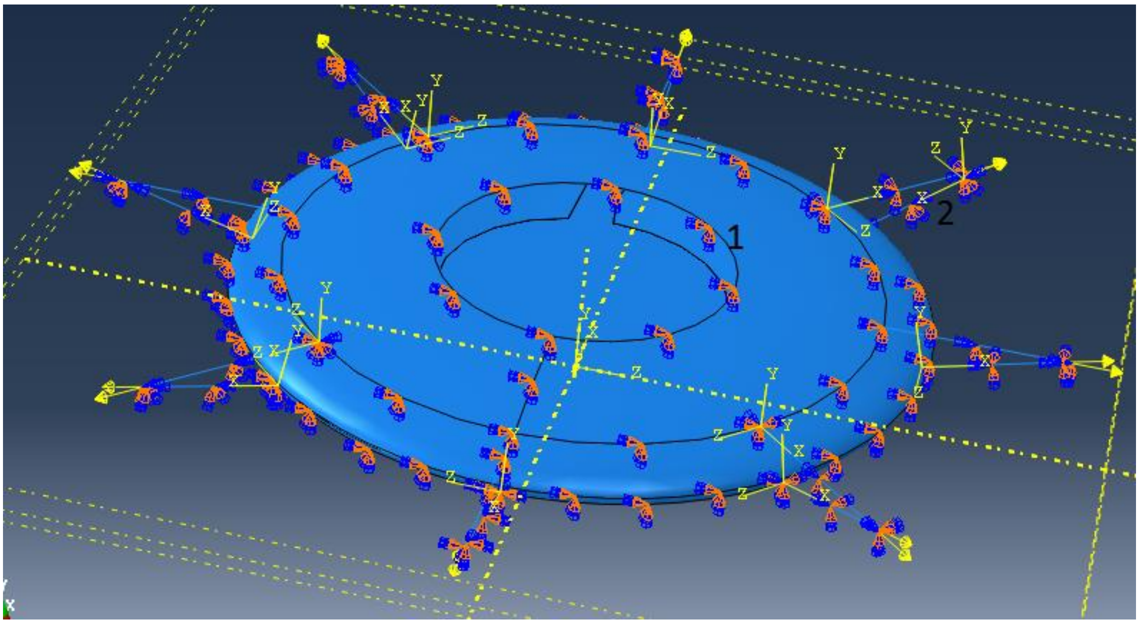

Figure 16. Boundary conditions of the model B

In terms of loads, there are sixteen load applying points in both models A and B. The load value is the same for both models and also for the sixteen points (ligaments insertionts in CB) in each model: 0.004875 N. This force is a sixteenth of 0.078 N which is, according to Lanchares *et al.* (2012), the zonular force necessary to reshape the model of a 30-yeard-old lens from the accommodated to the unaccommodated geometry. Also the article clarifies that nucleus and cortex of the crystalline lens become stiffer with age.

This force is applied in different point in model A and model B. On one hand in model A, as can be seen in figure 15, these loads are applied in every insertion – sixteen in total - of the ZF in the CB. On the other hand in model B the loads are applied at the end of each of the sixteen ZF as can be seen in figure 16.

4. Results and discussion

4.1 Results

As mentioned above, three different materials for the IOL have been used: PMMA, silicone and the natural material of human original lens. The three materials used have exactly the same points with maximum pressure, thus the only aspect in which they differ is the values.

4.1.1 Comparison among materials

First it is advisable to take a look at the differences among these 3 materials and later to focus on the one that is more adequate to analyse the stresses supported by the elements of the model.

Figure 17 shows the differences of stresses between the materials used. Stresses in the CB and in the IOL must be differentiated as despite the CB being exposed to the maximum stresses within this model and its values of stress seeming more decisive for the conclusions in order to assess the effect of the difference between the materials used for the IOL, the key factor is actually the IOL pressure.

Despite the fluctuations in the stresses in the CB the change is proportionally very small compared to the significantly higher variations observed in the IOL. While PMMA has maximum stresses of 154.6 kPa, silicone has maximum stresses of 17.36 kPa and crystalline lens 0.34 kPa.

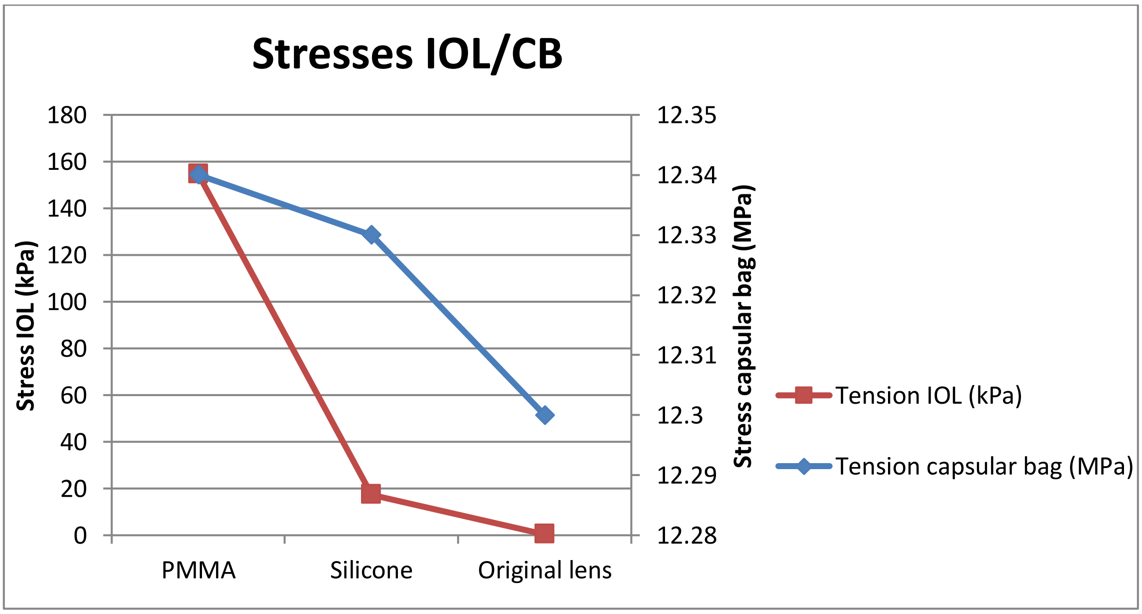

Figure 17. Maximum stresses in intraocular lens and capsular bag

4.1.2 Analysis of data

Based on the aforementioned results and literature research on the IOL materials, silicone was chosen as the material to build the model. As mentioned above, there are two models, A and B, and their analysis will be done separately.

- Model A: the lens, CB and ZF should be studied separately:
  - IOL (figure 18): there are two main points which suffer higher stresses than the rest of the lens. On one hand the end of the legs, which is in contact with the inner surface of the CB and on the other hand the area of more curvature of the legs, near to the optical zone of the lens, which is exposed to more stress as a result of the pressure of the CB, which leads to the legs being prone to closing. The 2 contact points with the CB register the highest stress detected in the IOL, and reached up to 17.36 kPa.
    In order to observe how the stresses are distributed along the IOL, switching to the right range of stresses show how the IOL works and which parts suffer high or low pressures. This is shown in figure 18, with a range between 10 kPa and 0.1 kPa.

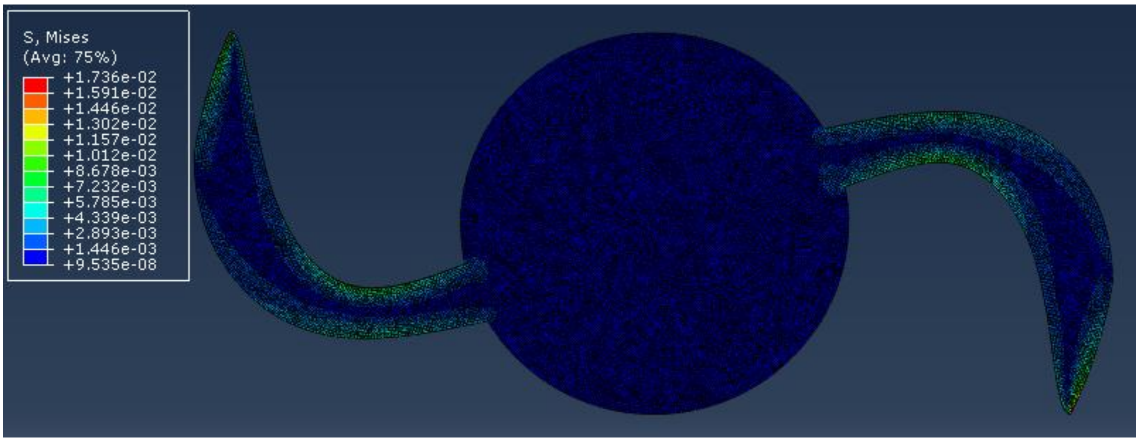

Figure 18. Stress suffered by the IOL

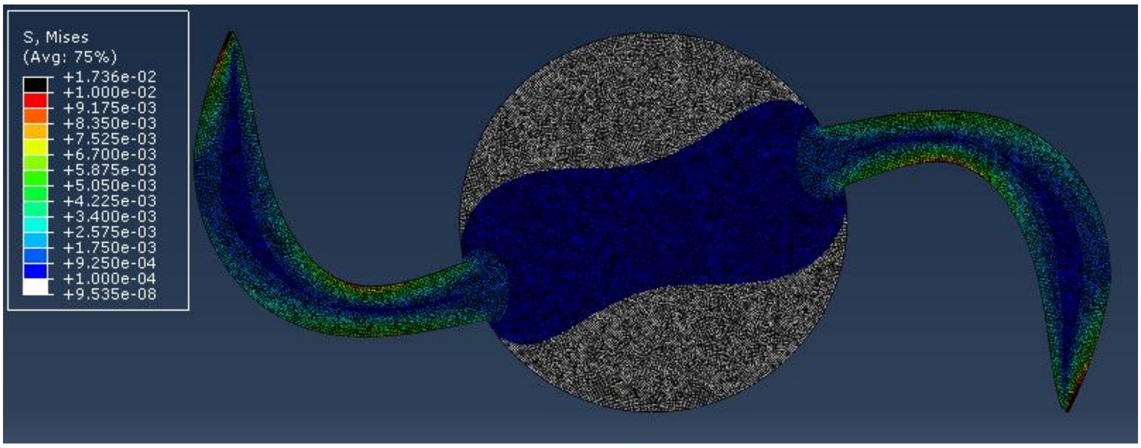

Figure 19. Stress between 10 kPa and 0.1 kPa are represented by scale of colours except for black (>10 kPa) and white (<0.1 kPa)

- ZF (figure 20): due to the asymmetric shape of the IOL, not all the ZF suffer the same stress values. In fact, almost every ligament is different from the others. Even so, the results are similar between them. The maximum value is 3.215 MPa and the minimum one 2.749 MPa.

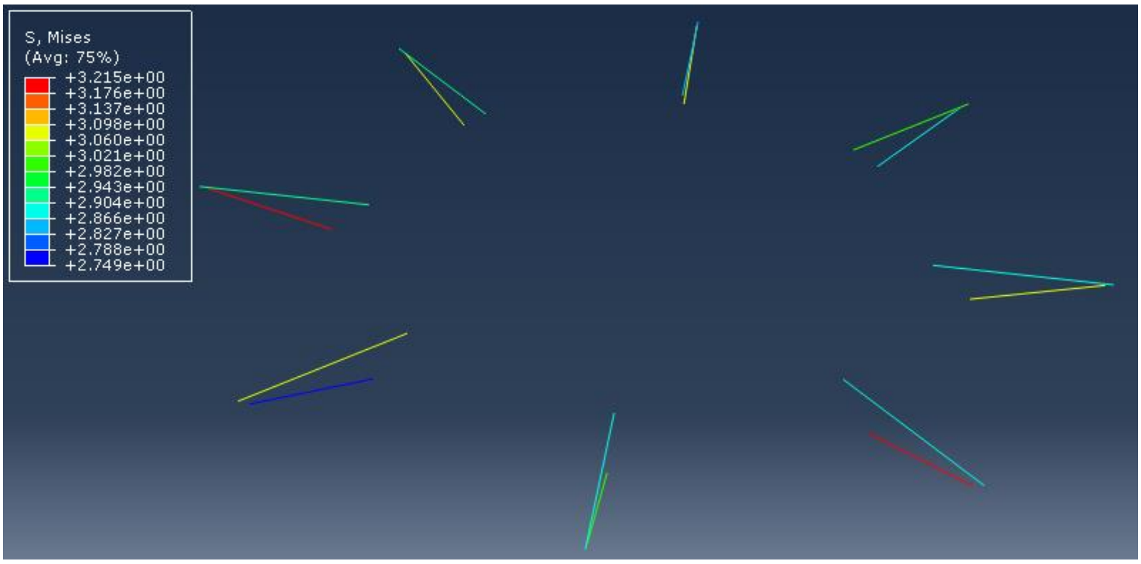

Figure 20. Stress suffered by the zonular fibres

- Capsular bag (figure 21): In CB is the highest stresses of this model. And there are sixteen main points where are high pressures. They are the insertion of the ZF in the CB, where is the maximum stress of the model: 12.34 MPa.

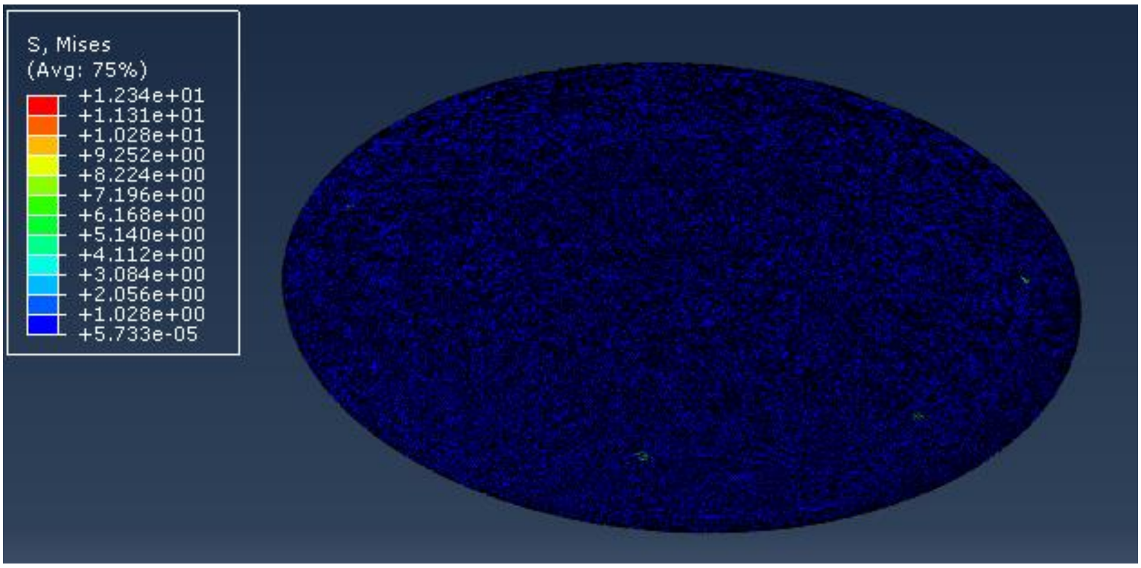

Figure 21. Stress suffered by the capsular bag

Figure 22 shows very good where are the highest pressures and how is the stress distributed there.

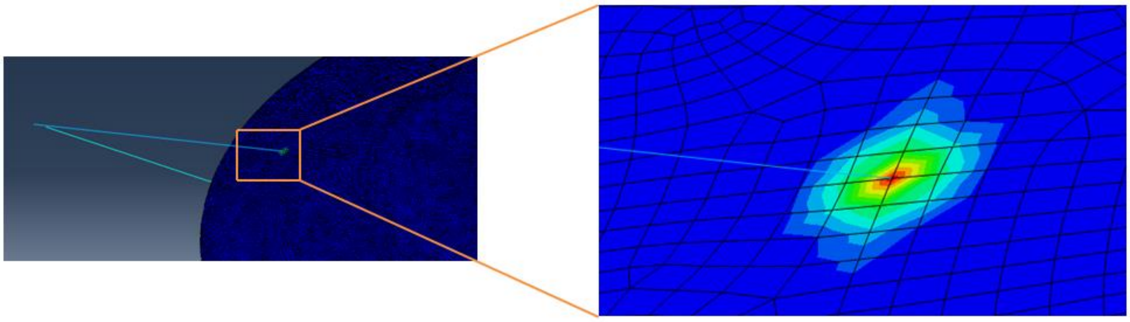

Figure 22. Enlargement of the model in intersection of zonular fibre with lens

However with the CB there is a big problem: as the forces are not real but resulting forces in the eight chosen axes, the stress in the insertions of each ligament are widely superior to the rest of stresses suffered by the CB. As a consequence, stress ranges were changed in order to gain a better observation of all stresses. The range chosen for that was between 10 kPa and 0.1 kPa as can be seen in figure 23. Looking at these results, it is clear that except from the ligament insertions, there are high stresses in the surface near to the centre circular hole. Also, there is a surprising data: one ligament insertion which has really low stresses apparently and appears with a blue colour what means that there is a very low stress. Everything was checked and there is no mistake, so it seems an ABAQUS error because is the CB is not symmetric but this difference is too big to analyse as something else than a mistake.

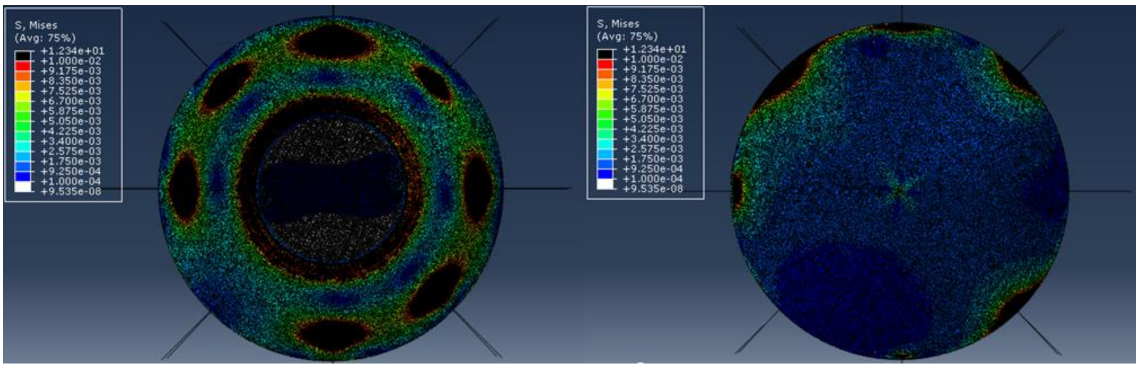

Figure 23. Stresses between 10 kPa and 0.1 kPa are represented by scale of colours except for black (>10 kPa) and white (<0.1 kPa)

As mentioned above, as the loads used are resulting forces of the absolute zonular force (which is the sum of loads in all the ZF), the stresses in the whole CB could be real except those suffered in the insertions of the ligaments. So it was necessary to change the loads (figure 24) in order to know approximately the stresses that suffered the insertion of ligaments in the CB.

This is dividing zonular force necessary for accommodation by the sum of anterior and equatorial zonules which are 100 and 50 respectively following table 5 in Annex A, so 150 zonules in total. This division has a result of 0.00052 N for each ligament. Also, model B was built on this new force because is focused on ligaments stresses, and those are more accurated. In this case, the stress in the insertion of the zonule in the CB is 1.316 MPa.

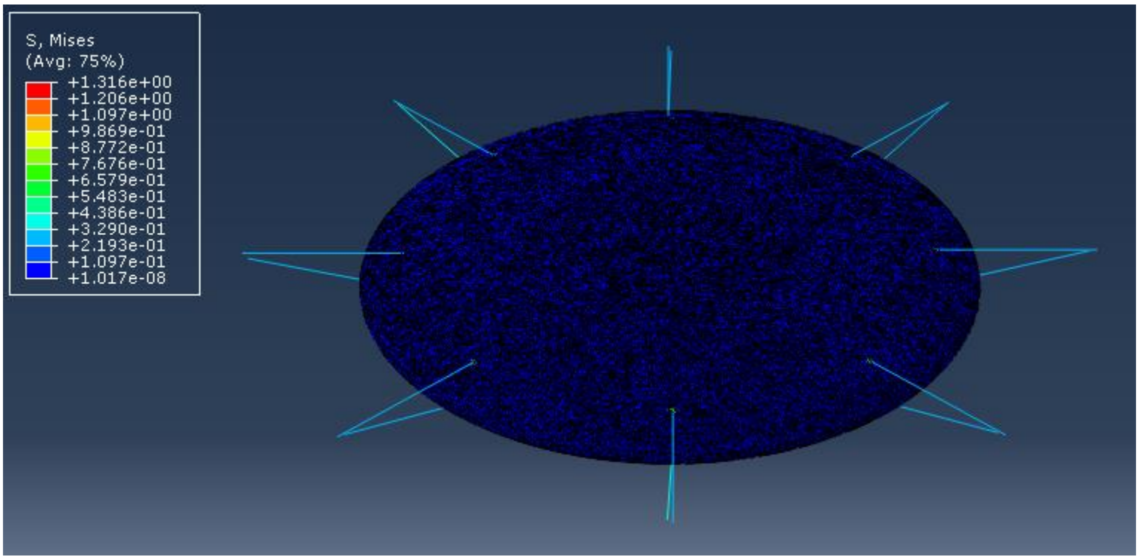

Figure 24. Model A with forces of 0.00052 N each ligament

- Model B: This has only stresses in ZF because an encastre boundary condition is used for the CB therefore there are no stresses in the CB and as a consequence neither there are in the lens. As expected, the stresses suffered by these ligaments are exactly the applied load divided by the surface (Pressure = Force/Surface) which in this case is the area of the ligament section. So that is:
  - For anterior zonules: 0.00052N / 0.00126mm^2 = 0.4138 MPa
  - For posterior zonules: 0.00052N /0.00196 mm^2 = 0.2648 MPa

4.2 Discussion

The results may need a comparison with some real values at similar models in order to prove their reliability and validity.

As a role model, the model built in the article mentioned above from Lanchares *et al.* (2012) was taken. This article includes three ways of reaching results (figure 25): numerical, FE model and cortex and nucleus. Among these three models, the FE model is the one which should has more similarities to the model built in this thesis. Comparing both models it can be observed that role model has 2 main points of stresses: the posterior part of the CB and connection points between CB and ZF. However, in the model built for this thesis, there is only one main point of stress: the connection points between CB and ZF. The reason of this difference between the two models could be the circular cut made during cataract surgery. Also it seems that the stresses that were supported by the posterior part in the role model moves, in the model of the thesis, to the surface surrounding the cut. This can be deduced because, even though with the colour scale generated automatically by ABAQUS (in figure 21) the different stresses of the model cannot be observed, it has been decided to change the colour scale to reduce the range between stresses maximum and minimum to see better the different pressures in the CB. This is represented in figure 23.

One of the problems arose due to the circular cut caused by cataract surgery. Doctors reported that due to the circular cut left by a cataract surgery the circular surface that remains in the CB tends to close over time, as the skin with any superficial wound of the body. It has not been possible to find the value of this force of the circular cut of the CB, and for convenience, it has been discarded. It is worth mentioning this points since it could have an impact on the final result.

Also worth noting that this thesis is directed to work on a problem (dislocation of the lens after cataract surgery) that does not have a clear solution nowadays. So this is a great handicap when it comes to finding information. There are many hypotheses on that, but still no one has the solution, and it is really difficult to measure the forces and stresses inside the eye as well.

It is well known that while something is investigated, there will not be lot of information available in internet because there are people still working on it, so if someone reaches some data or some good results, it is not going to publish until the end of the research.

The results obtained in this thesis seem quite adjusted to reality, but improvable. It has to been said that was not considered intraocular pressure caused by intraocular fluids.

The methodology used on this project was not ideal because of the lack of information in this field. Several assumptions and approximate measurements have been done in order to generate preliminary results.

Another aspect to take into account is everything that refers to ABAQUS. It was a new program for who writes this thesis, because at least in EEBE (Escola d'Enginyeria de Barcelona Est), this simulation program is not used. So, it was a great challenge but at the same time it has also involved an extra effort and a slow but profitable learning.

In addition, it would worth referring to the forces of the ligaments used in the project. As previously mentioned, the information is limited, and especially regarding the forces exerted by the ligaments. According to the only reliable source, which is the already mentioned scientific paper of Lanchares *et al.* (2012), the zonular force, which is the sum of the forces exerted by the anterior and equatorial zonules - in the case of non-accommodation stage - or the posterior zonules - in case of accommodation stage - is 0.078 N.

As we have not found information on how this force is applied, we have taken it and divided it among the 16 ligaments of the model (equivalent to the 150 in a real eye), thus applying the same force in the 16 ligaments. In reality that symmetry is rarely given, so it is another approach.

Once obtained the results, to have applied the resulting forces and not the real (for each ligament), it is decided to apply another assumption: divide the zonular force among the 150 ligaments. Once applied it can be seen the stress that is exerted on the CB approximately real, although it differs quite a lot from the forces obtained in figure 25. In spite of this, the stresses that do adjust quite to reality are those obtained in model B exerted on the ligaments. In this model the zonular force divided by the 150 ligaments is also used, and gives a resultant of 0.327 MPa.

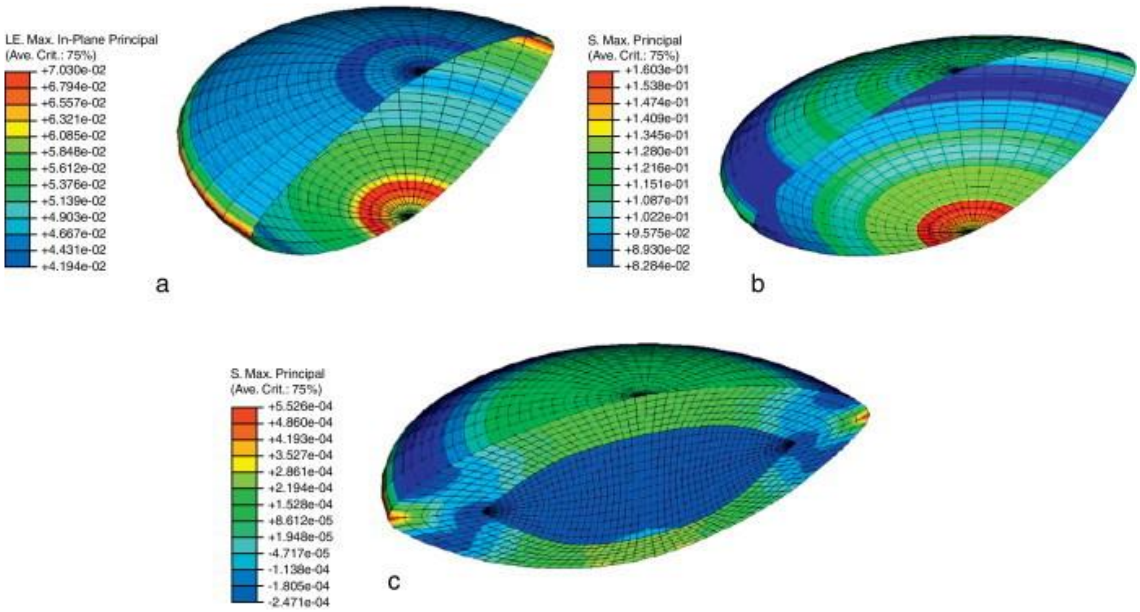

Figure 25. Maximum principal strain distribution of the capsule with FE model (a), numerical model (b) and cortex and nucleus (c) in the unaccomodated state of the 30-year FE model

Also it is fair to say that ages of some of the mechanical properties used are not specific. For example, the zonular force necessary to reshape the model of a 30-year-old lens from the accommodated to the unaccommodated geometry, so of course this could change over time. Also for the young modulus of CB there were only data for 20 year-old-people, 40 year-old-people and 60 year-old-people.

Furthermore, the movement in accommodation, as can be seen in figures 4 and 5, is a mechanism of more than one part in the eye. In this thesis was considered by mutual agreement with the doctors, to do this first step of the project with only ligaments, so the zonular force was focused only on the ligaments.

Finally, it has been said that building a completely real-based model would aloud to put all the forces and, even more important, observe stresses in CB and IOL in and hypothetical model B without encastre boundary condition, which did not allowed to see that.

5. Conclusions

A FE model regarding cataract surgery and problems with dislocations derived from this surgery has been developed and used to make predictions about stresses and pressures during accommodation focused on CB, IOL and ZF.

In order to work on this issue, three different types of IOL were analysed: a polymethyl methacrylate (PMMA) lens, a silicone lens and an IOL made of original human tissue, which does not exist but was considered in order to compare properties of human and artificial materials. The design of IOL is the same for the 3 materials and it was taken two of their mechanical properties, Young modulus and Poisson ratio.

The three parts of the model were modelled considering homogeneous and isotropic properties.

Among the two existing stages of accommodation, it was decided to build the non-accommodated stage, where the anterior and equatorial zonules are in tension and the posterior zonules are relaxed as can be seen in figure 4. For this reason posterior zonules were not modelled.

Despite values being important, the distribution of stresses along the CB, the ZF and the IOL play a more critical role due to lack of information in this field.

These stress distributions is what leads to conclude with the following hypothesis about the problem that has been studied in the thesis.

A natural lens, the one with which a human being is born, is circular and has a practically or totally symmetrical shape. The approximate pressure exerted on the inner surface of the CB is the same at all points.

But when the IOL is implemented significant changes occur. There are two areas of the CB that are exposed to considerably higher pressure than the rest. These two mentioned zones are where the legs of the IOL are in contact with the CB (see figure 1). The importance of this contact can be seen in figure 19 where the pressure distribution of the IOL is represented.

The two legs of the IOL play a key role on the stresses and can be observed in figure 3 as the stress suffered by the body (circular part of the IOL) traces a line of stresses from leg to leg, while the stress of the rest of the body lens being much lower.

As could be suspected, it depends on the design of the IOL, but most of these implants are designed with two legs, which lead to a redistribution of stresses.

As a result, the CB acquires a less circular and more oval shape over time. The ZF inserted at the point of maximum curvature of the mentioned oval CB suffer less stress while the ligaments inserted in the straightest area suffer more stress. It should also be noted that the hole left by the cut made during the operation of cataracts tends to close, which generates further stress in the ligaments.

This may eventually cause the ligaments in the area with less curvature to weaken and break over time.

If the ligaments begin to break, there will be fewer ligaments to support the same stress, thus fibres breakage is increasingly feasible. This steady loss of ligaments can lead to a dislocation of the lens.

This hypothesis is proposed as a possible cause of the dislocation of the lens. The information obtained about the major alternative hypothesis involving the intraocular pressure suggests that despite an increase in intraocular pressure during the days following the operation it will return to baseline – or even lower - after one or two weeks.

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ANNEX A

Element		Value	Reference
Crystalline lens	Young's modulus	see Table 3	Weeber et al. (2007a)
	Poisson's ratio	0.5	
Capsular bag	Young's modulus at 10% strain	1.5 N/mm^2	Krag (1996)
	Poisson's ratio	0.47	
Zonular fibres	Young's modulus	0.35 N/mm^2	Van Alphen (1991)
	Poisson's ratio	0.47	

Table 1. Mechanical properties of the three parts of the model

		Young's modulus [kPa]		
	Interval (mm)	20-year-old lens	40-year-old lens	60-year-old lens
Centre	0.000–0.441	0.043	0.814	108.544
	0.441–0.881	0.040	0.893	94.693
	0.881–1.322	0.057	1.084	79.077
	1.322–1.763	0.104	1.352	64.286
	1.763–2.203	0.200	1.663	50.246
	2.203–2.644	0.355	1.943	37.466
	2.644–3.085	0.517	2.061	25.996
	3.085–3.525	0.506	1.871	17.218
	3.525–3.966	0.308	1.417	10.817
Periphery	3.966–4.407	0.100	0.845	6.248

Table 2. Young modulus of the crystalline lens

Módulo elástico:

2.24 - 3.8 GPa

Coeficiente de Poisson:

0.384 - 0.403

Table 3. PMMA mechanical properties

Módulo elástico:

0.005 - 0.02 GPa

Coeficiente de Poisson:

0.47 - 0.49

Table 4. Silicone mechanical properties

Element	Value	Reference
Crystalline lens:		
Crystalline lens anterior radius	8.5918 mm	Dubbelman et al. (2005)
Anterior conic constant	− 3.5878	Dubbelman et al. (2005)
Posterior radius	5.0341 mm	Dubbelman et al. (2005)
Posterior conic constant	− 1.6666	Dubbelman et al. (2005)
Centre thickness	3.9831 mm	Dubbelman et al. (2005)
Equatorial diameter	8.8132 mm	Strenk et al. (1999)
Capsular bag:		
Anterior pole thickness	13 μm	Fisher & Pettet (1972)
Thickness at 7-mm anterior diameter	21 μm	Fisher & Pettet (1972)
Posterior pole thickness	3 μm	Fisher & Pettet (1972)
Zonular fibres:		
Number of anterior zonular fibres	100	Kaczurowski (1964)
Diameter	50 μm	Kaczurowski (1964)
Number of equatorial zonular fibres	50	Kaczurowski (1964)
Diameter	40 μm	Kaczurowski (1964)
Number of posterior zonular fibres	135	Kaczurowski (1964)
Diameter	40 μm	Kaczurowski (1964)
Anterior zonular insertion:	7.76 mm (diameter)	Farnsworth & Shyne (1979).
Posterior zonular insertion:	6.81 mm (diameter)	Kaczurowski (1964), Streeten (1978)

Table 5. Geometry of FE model according to Weeber *et al.* (2008)